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GROUND-WATER FLOW IN RELATION TO A FLOODING STREAM

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GROUND-WATER FLOW IN RELATION TO A FLOODING STREAM

David K. Todd[1] J.M. ASCE

Abstract

Quantitative data on ground-water flow during storm runoff periods are scarce. This study presents some information on the time distribution and magnitude of such flows based on model measurements. Idealized hydrographs and aquifers were studied in a Hele-Shaw viscous fluid model. Results of the model analogy are interpreted in terms of bank storage volume and distribution, and magnitude and time distribution of ground-water flow. Seepage bordering the Sacramento River is discussed in relation to the model data.

INTRODUCTION

Little is known of the ground-water contribution of stream flow during flood periods. Data are difficult to obtain in the field because of surface runoff and rainfall contributions, lack of sufficient permeability data, and expensive recording well systems. Then, too, long and irregular intervals between isolated high flows discourage detailed studies.

Because engineering investigations require estimates of total stream flow, the usual procedure in practice is simply to assume some reasonable value for base flow during high flow periods. Various methods have been recommended(1,8,13)2 for this purpose. It has been stated, and rightly so, that as long as one method is used consistently in any study, errors will be kept to a minimum. Such procedures are justifiable since: (a) detailed, accurate information is lacking; (b) the base flow contribution during a flood period is usually only a small fraction of the total flow; and (c) the accuracy of most stream-flow records does not justify any greater precision.

Previous investigations provide some clues to the true ground-water contribution. Hursh and Brater(5) analyzed field data and used the sharp break of the recession-hydrograph to locate the maximum on the normal ground-water depletion curve. Suter(15) presented data on flood hydrographs and nearby well stages of the Illinois River, showing how well levels rose and fell with the river. In an analytical treatment of waves in unconfined aquifers Werner and Noren(18) showed that harmonic oscillations of a stream were transmitted to the adjacent ground-water table where they were rapidly damped. Jones,(7) in a detailed study of the Upper San Joaquin River Valley, showed by profiles of ground-water levels that ground-water levels up to about one mile from the river were influenced by river levels. Hursh and Barnes(4) discussed the need for distinguishing ground-water flow from surface runoff, and the difficulty of separating interflow from base flow. Also,

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2. Numbers in parentheses refer to references at the end of the paper.

the question of the amount of temporary bank storage and of its return as subsurface flow was brought out. Based upon watershed studies in Switzerland and laboratory experiments, Roessel[12] indicated that base flow may well be a major part of flood flows, and that different runoff rates may occur from the same quantity of ground-water storage, depending upon the distribution within the aquifer of the water. Both Riesbol[11] and Snyder[14] made important contributions to the subject by their detailed analyses of watershed runoff.

Model Analysis

Because of the absence of field data for analyzing ground-water flows near a stream during periods of storm runoff, a model study was undertaken for this purpose. A Hele-Shaw viscous fluid model was utilized. This model consists of a channel formed by two closely-spaced glass plates through which a mineral oil flows. It can be shown that the laminar flow conditions obtained are analogous to ground-water flow conditions. The model design and applications have been described elsewhere;[16,17] while a similar model has been employed for base course drainage studies.[3] Solitary sine waves of varying amplitudes and periods were generated in a regulating reservoir at one end of the channel and allowed to travel into the channel containing a uniform oil depth. The conditions may be thought of as a model of a flooding stream with a rising and falling stage and having a horizontal water table intersecting the stream channel. Figure 1 shows a schematic diagram of the field conditions reproduced by the Hele-Shaw model analogy.

The model arrangement requires the following assumptions for analogous field conditions: (a) the stage hydrograph is of a sinusoidal shape; (b) an unconfined aquifer with homogeneous isotropic permeability exists adjacent to the stream channel; (c) the stream bank is vertical (corresponding to the reservoir-channel boundary); (d) the flood crest elevation is less than the ground surface so that no overflow occurs; (e) an impermeable horizontal bedrock coincides with the elevation of the stream bed; (f) the stream flow is much larger than the ground-water flow so that the stage is independent of any ground-water flows; (g) the ground-water table is initially horizontal; and (h) compressibility effects are negligible. These assumptions present idealized field conditions; nevertheless they enable quantitative ground-water flow measurements to be made on a model analogy basis. In essence, the model presents by analogy a vertical cross-section perpendicular to a stream channel.

During the time when various sinusoidal oscillations within the regulating reservoir were in progress, lapse-time motion picture records were obtained of the movement of the free surface in the channel. It should be noted that an oscillation is here defined as a fluctuation beginning at the initial minimum oil elevation in the channel, rising to a maximum elevation, and returning to the original minimum level. This corresponds to a sine curve extending from -90^{o} to $+270^{o}$. The amplitude is the difference in elevation between the minimum level (-90^{o}) and the maximum level (+90). Records of the oscillations showed that in the rising portion of the oscillation, oil flowed continuously into the channel. A reversal of flow in the second half of the oscillation became evident in that portion of the channel closest to the reservoir as the oil level in the reservoir decreased more rapidly than that in the channel. This process formed a wave crest which travelled from the reservoir into the channel and decreased in amplitude with time. Of interest here is the fact that the area, as viewed from the side of the channel, occupied by the oil

above the original constant oil level is analogous to the volume of ground-water storage induced by a flooding stream. From a graph showing the variation of this area with time, the derivative, or slope, of this curve represents the rate of change of area with time, or the ground-water flow rate. To study this flow distribution, 14 independent solitary sinusoidal oscillations in the channel were recorded and analyzed. Oscillation periods ranged from 2 to 6 minutes and amplitudes from 1 to 6 inches (2.5 to 15.2 cm). Included in Table 1, which summarizes all of the basic data, are tabulations of amplitude H, in cm, and period T, in min, for the various runs.

Since the model measurements cover different amplitudes and period of the same sinusoidal oscillation, it was desirable to express the results in terms of a general curve which would be applicable to all of the data. Reasoning that the volume of ground-water (or bank) storage is some function of the oscillation amplitude and period, Figure 2 was prepared. Here the maximum recorded volume V_{max} (from Table I) of storage, expressed in two dimensions as an area with units of cm^2, is plotted against the product of amplitude and period. It can be seen that a linear relationship is reasonably well defined by the model data, indicating that the parameter, V_{max}/HT, may be assumed constant for the various runs. Now since the time from the beginning of the oscillation of V/HT must depend upon the period of the oscillation, the dimensionless time parameter t/T may be introduced. Here V is the volume measured at time t after the start of the oscillation. Curves of V/HT versus t/T were prepared for the 14 runs and superposed; close agreement resulted. A mean curve prepared from the group of curves is shown as the "observed" curve in Figure 3. This volume-time curve begins at zero (since the oil volume below the initial constant oil level is neglected) and rises to a maximum at t/T = 0.56. This instant follows shortly after the time of crest stage in the reservoir (or stream, when speaking of field conditions) at t/T = 0.50. The volume then recedes toward zero, displaying a typical hydrograph shape. The curve is cut off after t/T = 5.0 as model data were not carried beyond this time.

The slope, or derivative, of the volume-time curve represents the ground-water flow. Since the volume to any time t may be expressed as

$$V = \int_{t=0}^{t} Q \, dt \qquad (1)$$

where Q is the ground-water flow occurring in any time increment dt, then the derivative of the curve in Figure 3 becomes

$$\frac{\frac{1}{HT} dV}{\frac{1}{T} dt} = \frac{1}{H} \frac{Q \, dt}{dt} = \frac{Q}{H} \qquad (2)$$

Hence, a graph of the parameters Q/H versus t/T should enable the time distribution of the ground-water flow for all of the runs to be compared.

An inspection of the slopes of Figure 3 indicates how the ground-water flow curves will appear. The derivative begins at zero, reaches a positive maximum at the steepest point of rise, returns to zero at the instant of maximum, goes to a minimum at the steepest point on the recession portion of the curve, and finally returns toward zero. For purposes of the ground-water analogy, signs of all ground-water flow curves will be reversed. By so doing ground-water recharge, or stream-flow loss, is given a negative sign; ground-water

TABLE I - SUMMARY OF BASIC DATA FOR SOLITARY

SINUSOIDAL FLOWS

Run No.	Amplitude, H, cm.	Period T, min	Max. Vol., V_{max}, cm^2	Q_{min}, cm^2/min	Q_{max} cm^2/min	t_{min} min.	t_o min.	t_{max} min.
1	7.6	3.0	379	-433	190	1.38	1.75	2.62
2	5.1	3.0	229	-389	129	1.25	1.50	2.25
3	7.6	3.0	419	-541	282	1.12	1.88	2.25
4	10.2	6.0	820	-606	184	2.25	3.20	5.25
5	10.2	2.0	445	-841	242	0.88	1.20	1.88
6	10.2	4.0	651	-587	352	1.50	1.70	3.50
7	5.1	3.0	256	-361	159	1.38	1.70	2.50
8	15.2	3.0	872	-1102	421	1.25	1.80	2.50
9	2.5	3.0	148	-230	30.5	1.12	1.50	2.75
10	10.2	3.0	535	-701	253	1.25	1.70	2.75
11	2.5	3.0	101	-120	35.0	1.38	1.50	2.75
12	12.7	3.0	714	-831	355	1.25	1.75	2.62
13	10.2	3.0	548	-741	268	1.25	1.70	2.50
14	10.2	5.0	742	-608	254	1.62	3.25	4.00

discharge, or stream-flow gain, becomes positive. This convention is in accord with the usual concept of treating ground-water flow into a stream as a positive contribution.

To verify the above indicated comparison, computed maximum and minimum discharges, Q_{max} and Q_{min}, respectively, were plotted against the oscillation amplitude, H. The minimum discharge may be regarded also as the maximum recharge. The results, using data from Table I, appear as Figure 4 and support the contention that the parameter Q/H may be assumed constant for the various runs. Similarly, if the times, t_{min}, t_o, and t_{max} (see Table I), correspond to Q_{min}, Q_o (zero flow between recharge and discharge), and Q_{max}, respectively, then these times should also bear linear relationships to the oscillation periods. The data plotted in Figure 5 substantiate this supposition—Q_{min} takes place at t/T = 0.41, Q_o at t/T = 0.56, and Q_{max} at t/T = 0.86. Based upon these comparisons among the different runs, the 14 discharge curves computed from the volume-time curves likewise showed substantial agreement when plotted in terms of Q/H versus t/T. The mean curve, and derivative of Figure 3, appears as Figure 6.

Although the exact magnitude of ground-water flow adjoining a stream always has been difficult to ascertain, the flow reversal shown by Figure 6 was recognized by earlier investigators. Brater[2] in 1940 stated that when a stream rises above the adjacent ground-water table, "---there must be a temporary reversal in the ground-water gradient and the ground-water contribution could conceivably be negative for a short interval." Other engineers (8, p. 399; 13, p. 266) also have correctly interpreted this phenomenon.

Regarding the scatter of data indicated in the previous figures, errors may be attributed largely to instrumental and analytic sources. The flow rate of the oil between the glass plates is a function of density and viscosity of the oil. Temperature modifies both of these properties; hence all data were corrected from the observed temperature to a standard of 70°F. However, if the oil temperature in the course of an oscillation changed, the single observed temperature would not correctly account for these effects. Errors also may have been introduced by small deviations from the true sinusoidal pattern, since the unsteady flows were manually controlled by inflow and outflow valves connected to the reservoir. Areas of oil were scaled from projections of the 35-mm film record by measuring ordinates at 6-inch intervals along the channel. A grid sheet attached to the back of the glass channel aided in scaling off the ordinates. Measurements were accurate to about 0.15 cm.

The far end of the channel, opposite to the reservoir, was left open except for an overflow lip fixed at the same elevation as the initially constant oil level. This end of the channel could not be sealed without violating the assumed field analogy (Figure 1). The fact that the channel was of a finite length and not of a semi-infinite extent as previously assumed, introduced erroneous volume and flow values. Fortunately, errors did not begin until the oil level had begun to rise and outflow ensued at the far end of the channel. This happened near the middle of the recession portion of the discharge curve. The nature of this limitation may be ascertained from a knowledge of the flow pattern. As the oscillation occurs within the reservoir a wave is propagated into the channel which damps out along the horizontal oil surface at a theoretically infinite distance. Practically, however, the damping rate is very rapid and changes of the oil level become negligible in relatively short distances. The effect of the outflow error was to reduce the oil area within the channel at a faster rate than would have resulted if a longer channel had been used, and to give too large a discharge in the recession portion of the discharge curve.

In an effort to evaluate the magnitude of the error, the recession portion of Figure 6 was plotted on logarithmic coordinates (Figure 7). This showed that the data closely fitted an equation

$$\frac{Q}{H} = 16.2(t/T)^{-2.76} \tag{3}$$

except for a sharp break near t/T = 1.8. Examination of the data showed that this time closely corresponded to the initial outflows at the far end of the channel. Hence it is reasonable to assume that if this flow had not occurred, the logarithmic recession curve, labelled "computed" on Figures 3, 6, and 7, would have continued. It is believed that this computed curve more nearly represents the true conditions pertaining to a semi-infinite aquifer. The flows indicated by the difference between the observed rate and projected logarithmic rate form a small hydrograph with rising and falling limbs. Outflow at the far end of the channel amounted to 9.8 percent of the total inflow volume up to t/T = 5.0.

Figure 8 shows typical dimensionless stage hydrographs of the oil (water table) at distances of 0, 0.5, 1.0, 2.0, and 5.0 feet from the reservoir. The height h occurs at the time t and is always less than H away from the stream channel. These curves illustrate the rapid damping of the oscillation as it travels from the source.

Model-Prototype Relations

To interpret properly the model results they must be expressed in terms of similar prototype conditions. This can be done by assuming length and time scale ratios, and solving for prototype velocities, discharge, and permeability.

The mean velocity of flow in the model may be expressed by

$$V_m = \frac{\rho_m b^2 g}{3\mu_m} \frac{dh}{dx} \tag{4}$$

where ρ_m is the oil density, μ_m is the oil viscosity, b is the half-width of the channel spacing, g is gravity, and dh/dx is the surface slope.[17] Similarly, the velocity of flow in an aquifer may be expressed by the Darcy law as

$$V_p = \frac{\rho_p k g}{\mu_p} \frac{dh}{dx} \tag{5}$$

where ρ_p is the density of ground water, μ_p is its viscosity, and k is the aquifer permeability (expressed as an area). The ratio of these two velocities when governed by the same slope becomes

$$\frac{V_m}{V_p} = V_r = \frac{\rho_m b^2 \mu_p}{3\rho_p k \mu_m} \tag{6}$$

where the subscript "r" denotes a model-prototype ratio. For the mineral oil used in the model, ρ_m = 0.877 gm/cc and μ_m = 1.016 poise at 70°F. The plate spacing was 0.2096 cm, so that b = 0.1048 cm. At 70°F for water,

ρ_p = 0.998 gm/cc and μ_p = 0.00979 poise. To obtain a value for k in equation (6), V_r must be known. This quantity depends upon the length L_r, and time T_r, scale ratios. Values of L_r = 0.01 and T_r = 0.0003 may be assumed for illustration and to give information of the correct order of magnitude of prototype conditions. Thus, the model channel with a length of 10 feet represents a 1000-ft. distance on one side of and perpendicular to a stream channel, while a 3-inch oscillation is equivalent to a 25-ft river stage fluctuation. Similarly, a 3-min oscillation is comparable to a storm runoff duration of 6.9 days. Inserting these values to find V_r gives

$$V_r = \frac{L_r}{T_r} = \frac{0.01}{0.0003} = 33.33 \qquad (7)$$

Using this value in equation (6), together with the other known data, gives a permeability of 9.29 x 10^{-7} cm^2, or 94.2 darcys. A 40-mesh sand, packed to a 40 percent porosity, would have roughly the same permeability (9, p. 113).

If field data happened to be available so as to provide an estimate of k, then V_r could be computed directly. Knowing V_r, L_r and T_r could be selected to study any desired flood amplitude and duration.

Bank Storage

Estimation of the volume of bank storage for assumed prototype conditions may be made from Figure 3. Direct conversion by means of the length scale cannot be made without a further assumption of specific yield. In the model channel the specific yield has been implicitly taken as 100 percent. This is true if the small adhesive oil film on the glass surfaces is neglected. A value of 10 percent specific yield may be assumed as a constant for field conditions. It has been pointed out by Jacob (13, p. 384) that the amount of water draining per unit volume of aquifer during the lowering of a ground-water table is a function of time. The maximum amount drained equals the specific yield. With the constant value of 10 percent specific yield, it is here assumed that the water will flow completely into and out of the aquifer with equal ease. The error incurred by this assumption will be small in this illustration because of the long time involved in the prototype ground-water flow. A large storm runoff of minimum duration would provide the least drainage time and hence give the largest error due to a variable storage coefficient.

As shown by Figure 2 the volume of ground-water recharge, or bank storage, is directly proportional to the amplitude-duration product of the storm runoff. For illustration the previously described 25-ft and 6.9-day runoff may be used. Converting the recharge and discharge from Figure 6 by means of the length and time scales, and multiplying by the specific yield, gives for the maximum recharge 0.00278 cfs per lineal foot of stream channel; 0.00109 cfs/ft for the maximum discharge. The total volume of recharge amounts to 421 ft^3 per lineal foot of stream channel.

Expressing the above results in more meaningful units and taking into account that the identical phenomenon is taking place within the opposite stream bank, the maximum ground-water recharge rate equals 29.3 cfs per mile of stream channel; the maximum discharge, 11.5 cfs/mi. It should be noted also that for this example, the peak stream flow occurs 3.45 days after the start, the maximum recharge occurs after 2.8 days, the flow reverses at 3.9 days, and the maximum discharge occurs after 6.0 days. Measurable return flow

to the stream persists for several weeks. The total recharge volume amounts to 102 AF per mile of stream channel.

Bank storage occurs in that portion of the aquifer closest to the stream channel. Previous study(17) has indicated a very rapid decrease in the amplitude with distance inland. Rough calculations for the conditions described in the above illustration indicate that 50 percent of the total bank storage is contained within the first 175 feet of the channel, and 75 percent within 350 ft.

Sacramento River Seepage

An interesting field problem related to the topic of the model study is that of the Sacramento River seepage. During seasons of high runoff, Sacramento River stages below Shasta Dam exceed the adjacent land surface. An extensive levee system ordinarily confines the high flows to within the levees. Landowners of the strip of land adjoining the river and outside the levees, however, contend that "when the water surface is carried well above the outside land surface for any substantial number of days, the pressure forces the water to seep underground and saturate and waterlog the land to an extent that it cannot be worked or pastured and damages the orchard crops and kills the trees".(6) The Corps of Engineers has been studying the problem from a flood control standpoint, while engineers of the Bureau of Reclamation have made extensive measurements of the seepage because some parties have expressed the opinion that controlled releases of Shasta Dam have contributed to the problem. A committee of the California Legislature has recently looked into the problem,(6) and at the present time the California Division of Water Resources is analyzing all available data in preparation for a final report.

This particular problem provides a good illustration of the difficulties typically encountered in applying laboratory results to subsurface field investigations. Data collected by the U. S. Bureau of Reclamation provide an insight into the situation.(10) Shifting of the river channel in the past has produced irregular lenticular deposits of gravel, sand, silt, and clay. The surface material is predominantly fine-grained with scattered gravel and/or sand deposits to be found in the upper 100 feet. Because of the concern for seepage on agricultural land bordering the river, lines of wells were established by the Bureau at several points along the river. The lines extend inland from the levee and water table elevations were observed daily for long periods.

These observations showed that the ground-water table adjacent to the river was governed by rainfall, irrigation, river stage, and geology. The variability of these factors in either space or time indicate the complexity of the problem. The water table approximates the river stage. In summer and other periods with the river stage low, the water table is maintained by irrigation and is higher than the river. Drainage is then toward the river. During periods of high stages, the river level exceeds the water table elevation and recharge, or seepage, occurs. Water table elevations have been observed to change up to 10 feet within 5 days due to varying river levels. Amplitudes of fluctuations decrease inland, extending as far as 1/2 to 1-1/2 miles, depending upon locality. Depths to water table vary in extremes from zero to 25 feet in the river influence area.

Figure 9 shows a small portion of the data. River and nearby water table elevations at West Wilkins Slough for the spring of 1945 are shown. Well No. 1 is located only 100 feet from the levee, Well No. 4 is 600 feet, and Well No. 5 is 1100 feet. Precipitation and well logs are included for completeness. It

can be seen that three major river rises occurred, affecting the nearest well most and the farthest well least. Until about April 1 a good correspondence between the river stage and the water table is apparent. Well fluctuations follow those of the river, delayed slightly with time and decreasing with amplitude inland. After April 1, Well Nos. 4 and 5 show a rise not indicated by either the river stage or Well No. 1. Presumably early irrigation is responsible for this deviation since rainfall is negligible.

The river stage continuously exceeded the ground water table elevation (Well No. 1) at this point in the 1944-45 season from November 3, 1944 to April 14, 1945. If the correspondence between the river and wells is taken as an indication of direct connection of permeable strata, a large recharge from the river may be expected. The available well logs, however, indicate rather tight formations so that a quantitative estimate of recharge is difficult to make. No direct application can be made of the model results in this instance because of the vertical recharge of the aquifer by rainfall and irrigation. Then, too, the inland water table may be regulated by Wilkins Slough, which parallels the well line and intersects the river about 900 feet southward, or by inland drainage systems.

Although the model results cannot be applied directly, an interesting comparison should be noted. Field studies by the Corps of Engineers have shown that the amount of seepage is roughly proportional to the number of days river stages are above natural bank levels and to the number of feet the river stage exceeds those levels (6, p. 25). This "foot-days" factor is analogous to the amplitude-period product which was shown by Figure 2 to be directly related to the total ground-water recharge.

Discussion

Although the model data lead to idealized results in terms of field conditions, they nevertheless describe for one of the simplest cases the distribution of ground-water flow. Variation of any of the controlling factors will modify the results herein presented. Storm rainfall is implicitly assumed to have fallen over some portion of the drainage basin upstream from the cross-section studied. Vertical percolation and interflow may be regarded as distinct stream-flow contributors and have been eliminated from the present study. Other hydrograph shapes will yield different ground-water storage and flow curves.

The model results showed that recharge and discharge were directly proportional to the amplitude-period product. In the field this may be interpreted by saying the ground-water recharge and discharge are directly proportional to a stage-duration factor. At a given point on a stream isolated storm events occurring over the drainage area above a given point on a stream would result in approximately constant flood durations, as indicated by the unitgraph theory. In such instances the ground-water recharge and discharge would depend only upon the flood stages, so that by means of a rating curve at that point, an approximate relationship between the stream flow and the ground-water flow could be established.

The model experiments required a horizontal ground-water table in equilibrium with the stream in the prototype situation. This would only rarely occur in the field. The more common situation where the ground-water table and stream are in contact would be an influent or an effluent stream. Here the ground-water table slopes upward or downward to the stream surface, respectively. As a first approximation for such cases the effects may be

considered as additive, so that the ground-water flow curve would be shifted upward for effluent streams and downward for influent streams. Depending upon the relative magnitude and direction of the initial ground-water flow to the maximum recharge and discharge rates, flow reversals may or may not result from storm runoff.

The initial ground-water depth was taken as constant for all model runs. For completeness this depth also should be investigated because its variation affects flow rates. For these unsteady flows the ratio of amplitude to depth is a complex function of the flow, and no general statements can be made about the magnitude of this effect.

The ground-water contribution to a storm hydrograph at a given point on a stream is the combined effect of all ground-water flows upstream of that point. Thus the recharge-discharge pattern discussed herein is in phase with the crest stage, so that the flow depends upon the location of the flood crest. A complete analysis involves the integrating time distributions, aquifer and permeability variations, tributary effects, and changes in the storm hydrograph with travel. Although the generalized results presented in Figs. 3 and 6 are applicable only with respect to the assumptions stated, they nevertheless should aid toward a better understanding of ground-water flows bordering on a stream channel. Extending or modifying the analyses to suit particular problems may permit estimates of ground-water flow to be prepared.

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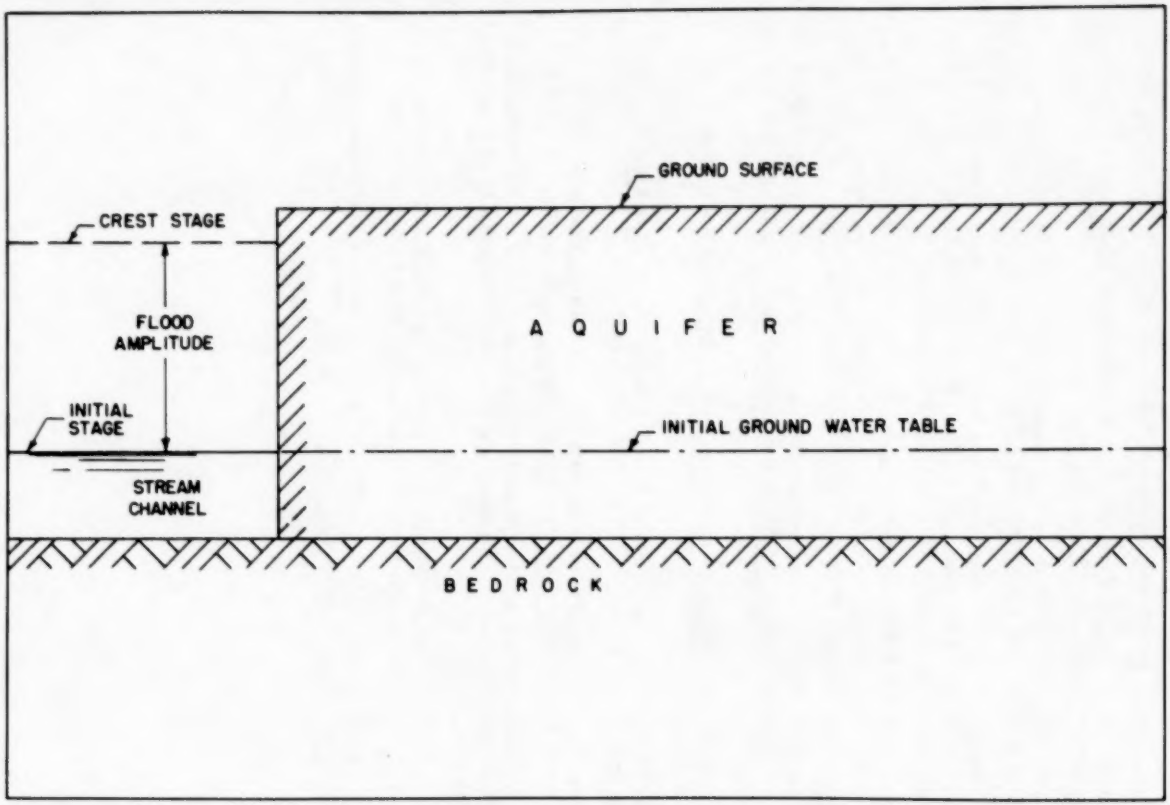

Fig. 1. Schematic diagram of vertical cross-section showing field conditions simulated by the Hele-Shaw model analogy.

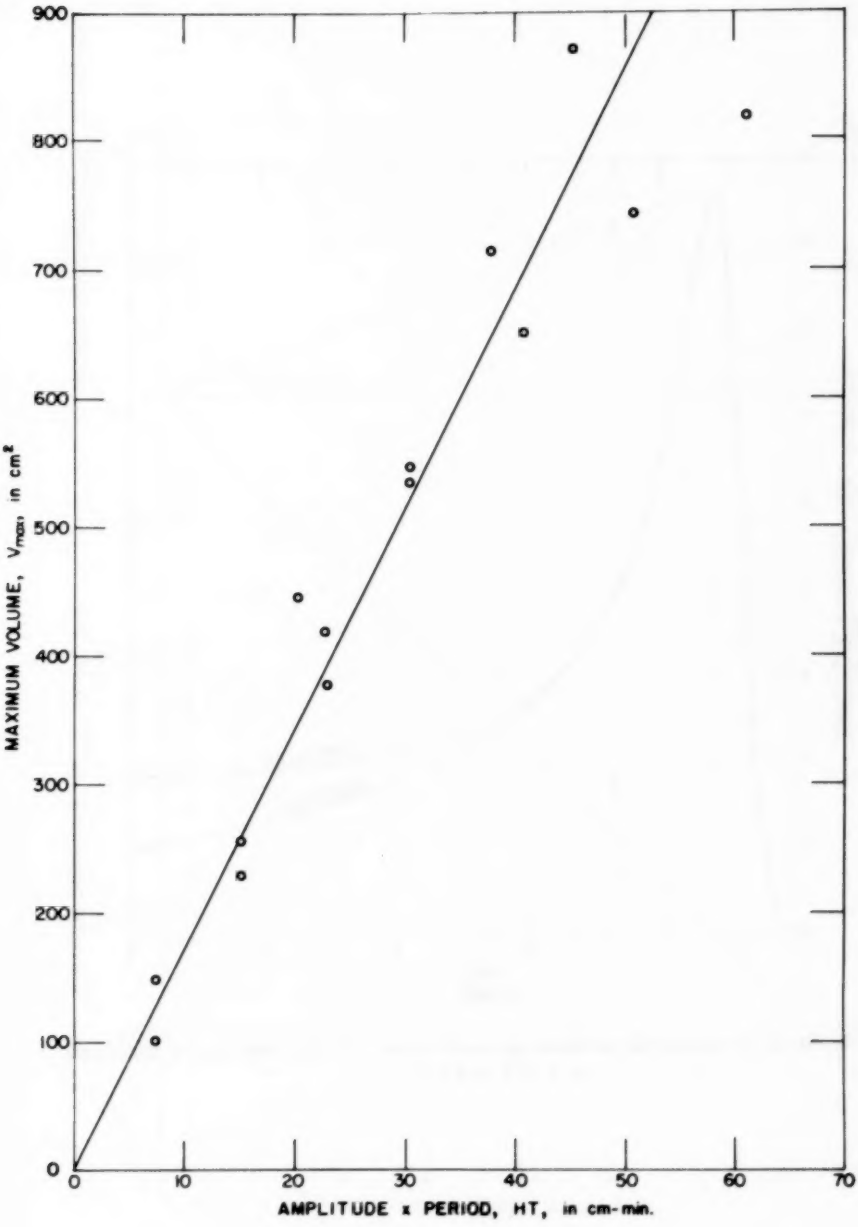

Fig. 2. Relationship of the maximum volume of ground-water recharge to the product of amplitude and period of stream oscillation.

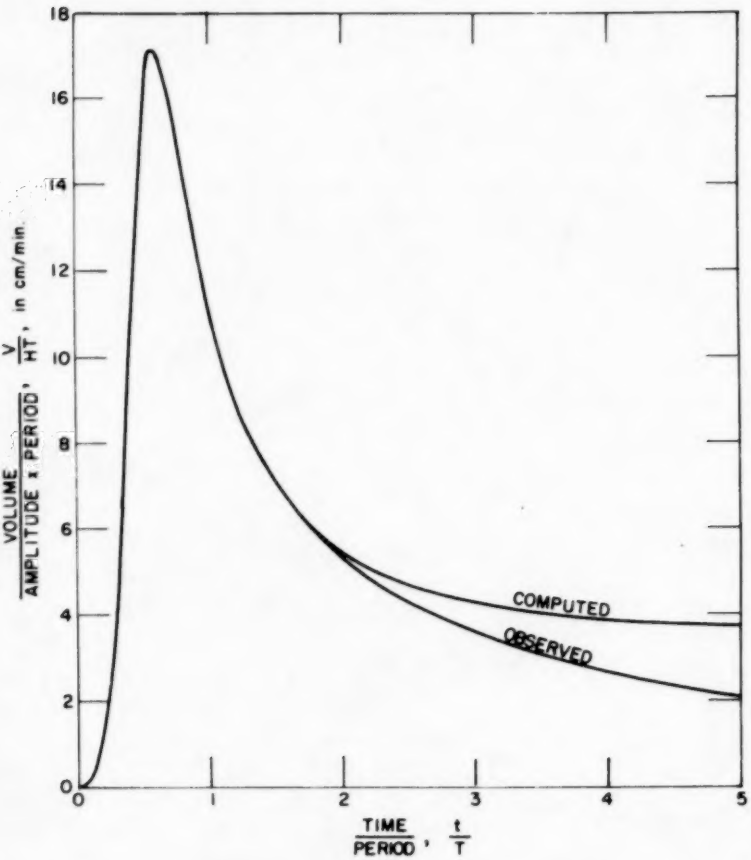

Fig. 3. Mean relationship between ground-water volume and time expressed as V/HT and t/T.

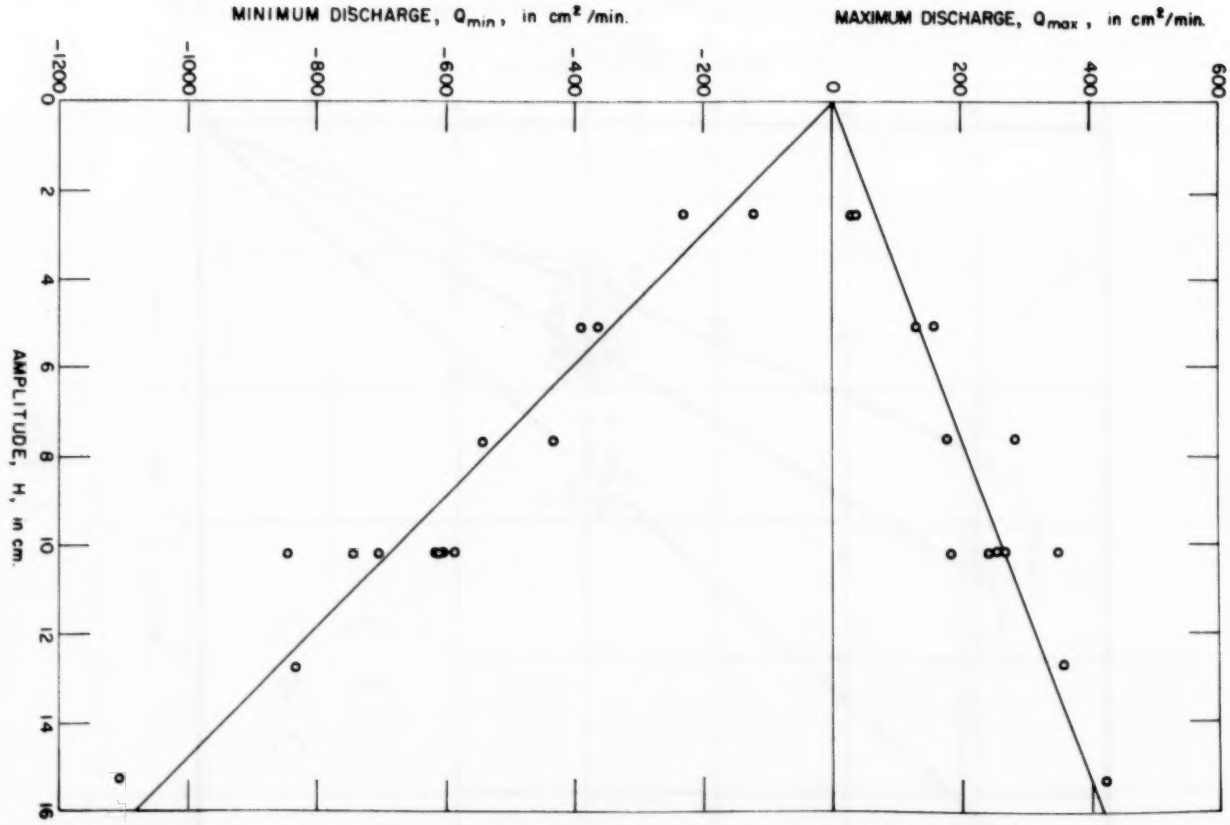

Fig. 4. Relationship of maximum and minimum ground-water discharge to amplitude of stream oscillation.

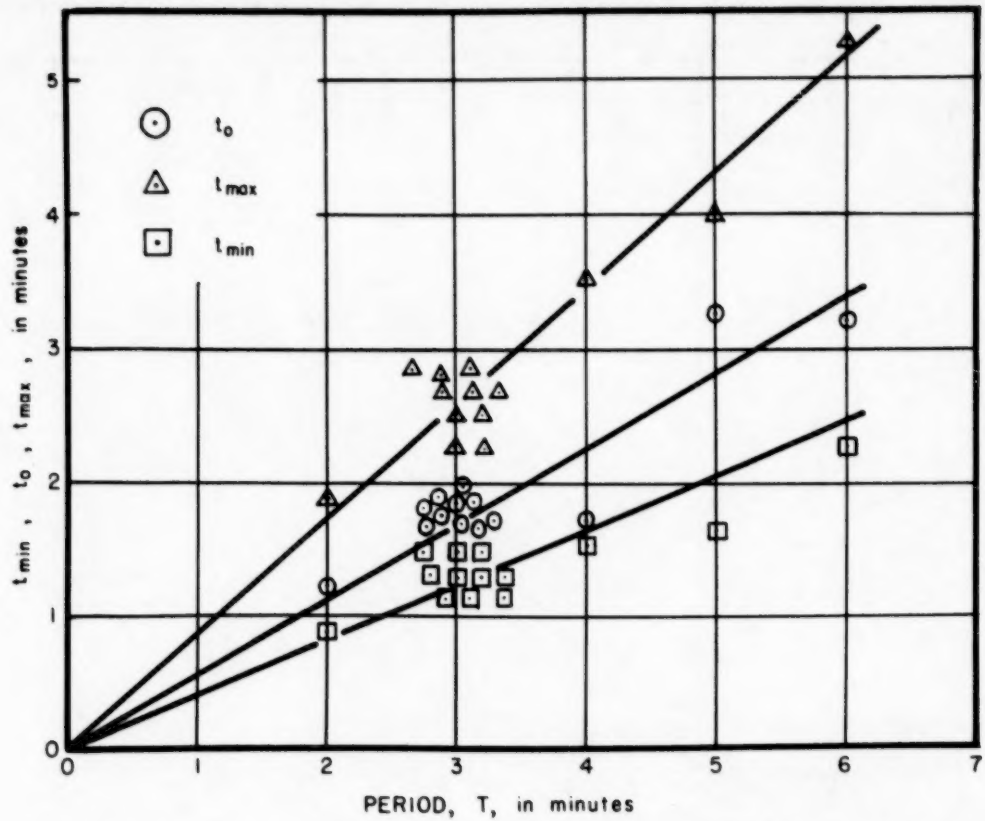

Fig. 5. Relationship of times t_{min}, t_o, and t_{max} to the period of stream oscillation.

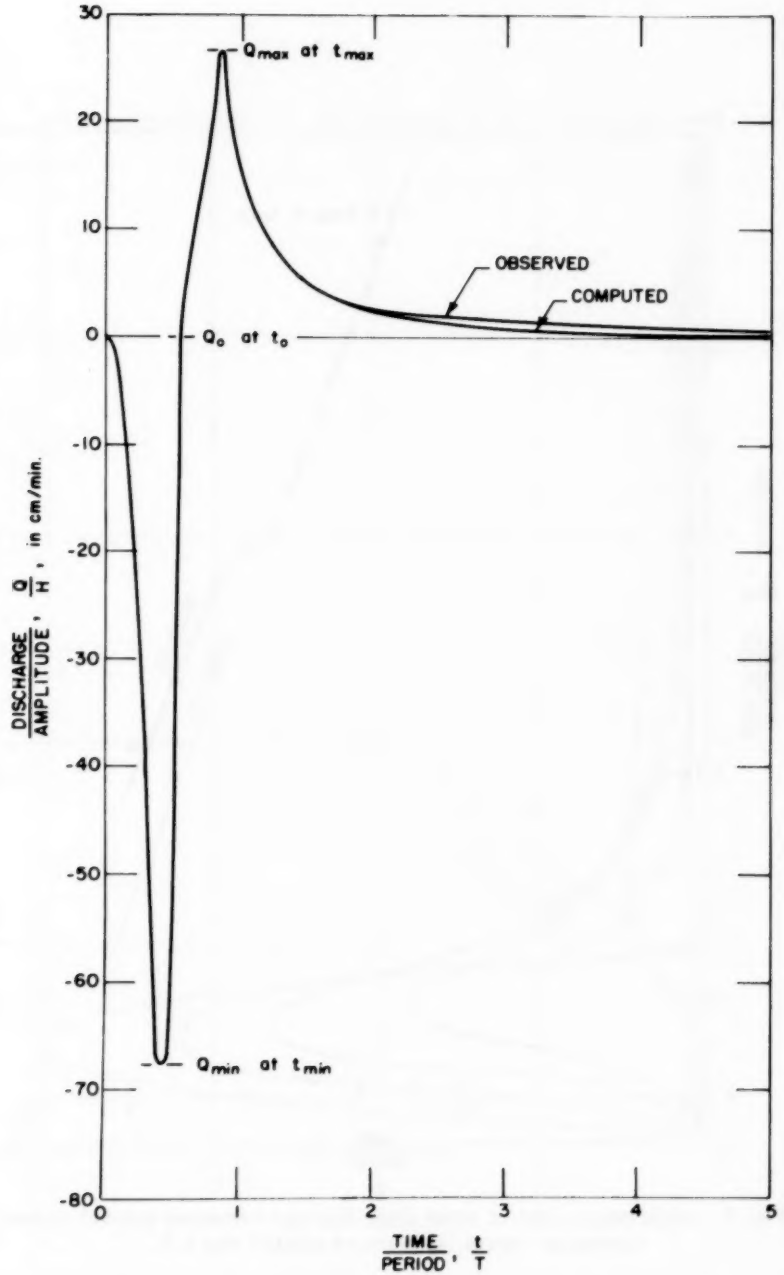

Fig. 6. Mean relationship between ground-water discharge and time, expressed as Q/H and t/T.

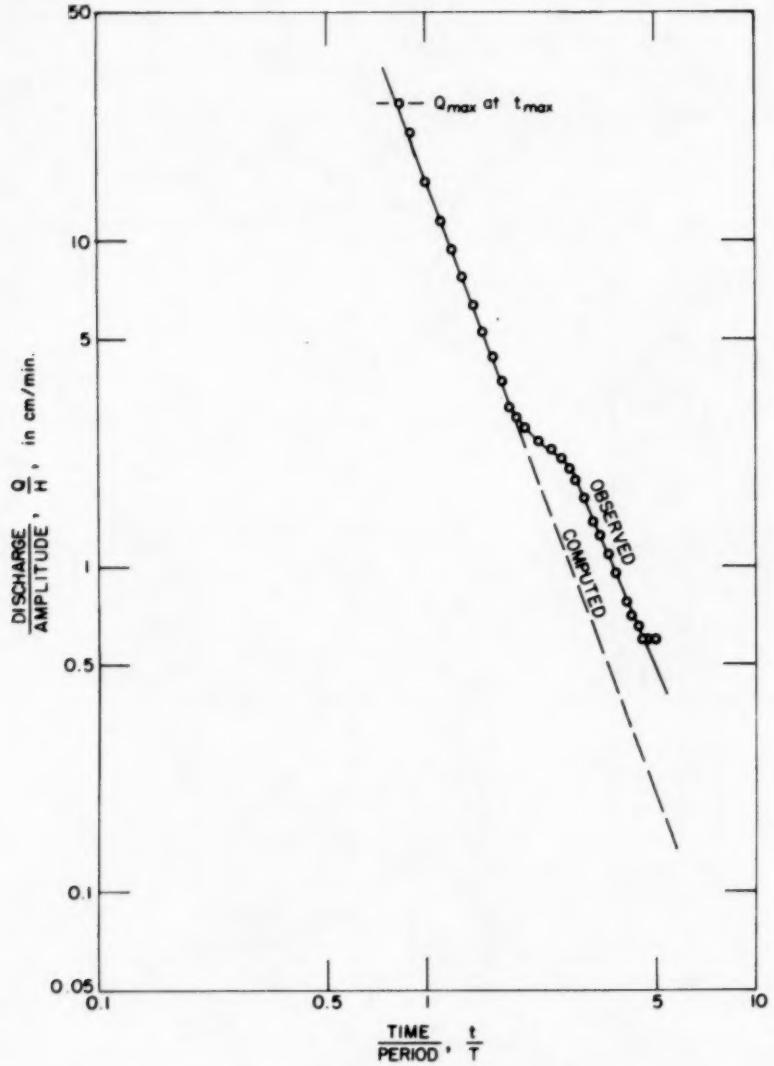

Fig. 7. Logarithmic plot of mean observed and computed ground-water recession curves, expressed as Q/H and t/T.

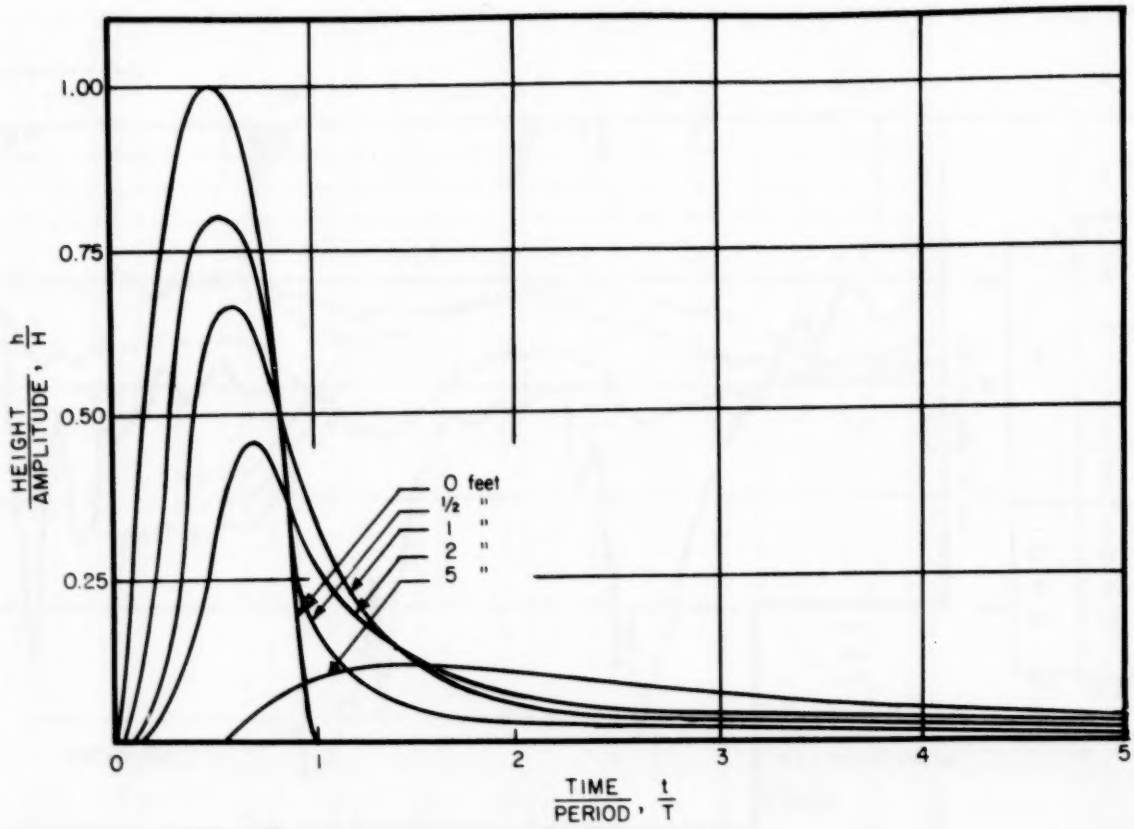

Fig. 8. Mean ground-water table hydrographs at various distances from the stream channel, expressed as h/H and t/T.

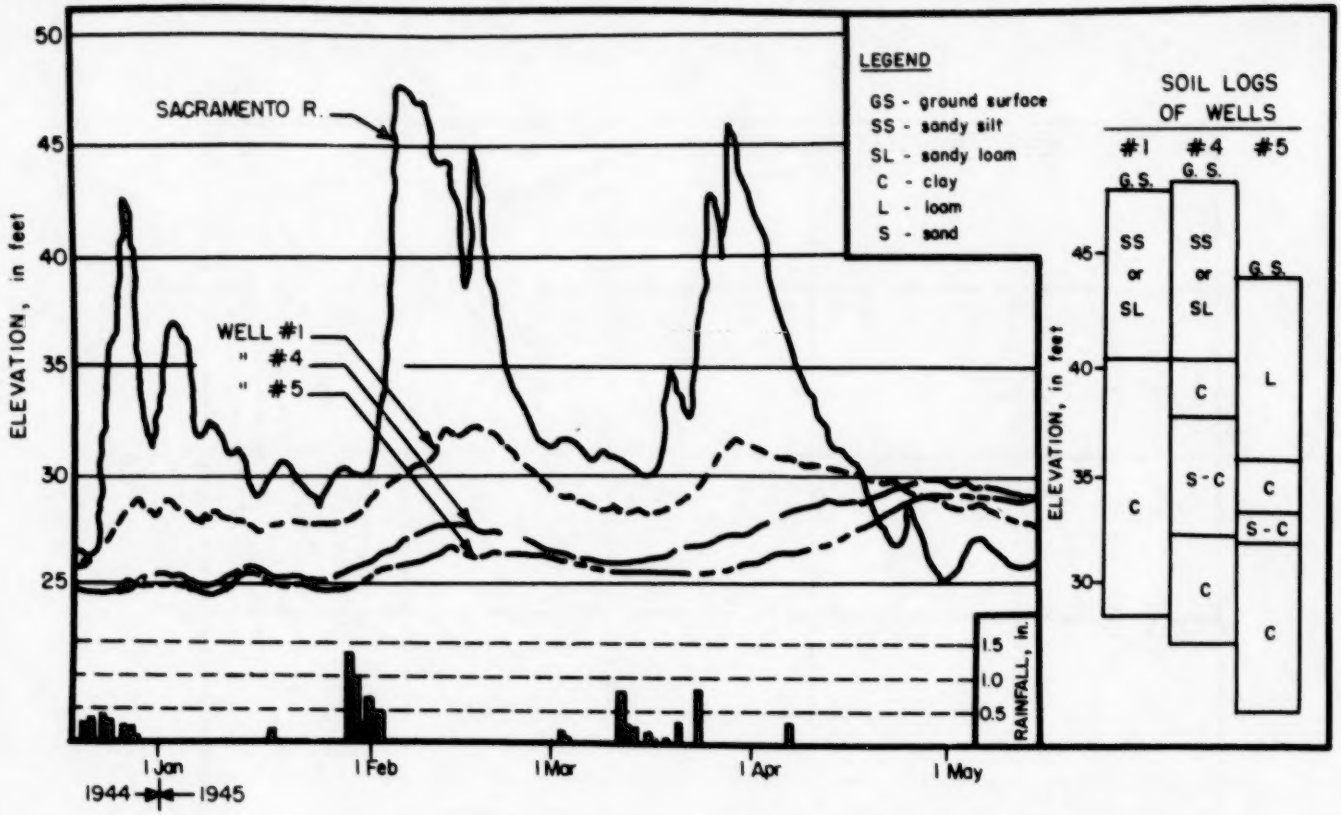

Fig. 9. Stage and ground-water table hydrographs, Sacramento River at West Wilkins Slough, California.

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c. Discussion of several papers, grouped by Divisions.
d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.
e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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